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Limits on short-range spin-dependent forces from spin relaxation of polarized ^3He

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Abstract

A new limit is presented on the axion-like monopole-dipole P,T-non-invariant coupling in a range ($10^{-4} - 1$) cm. The gradient of spin-dependent nucleon-nucleon potential between ^3He nucleus and nucleons and electrons of the walls of a cell containing polarized ^3He gas should affect its spin relaxation rate. The limit is obtained from the existing data on the relaxation rate of spin-polarized ^3He .

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A number of proposals were published for the existence of new interactions coupling mass to particle spin [1, 2, 3, 4]. On the other hand, there are theoretical indications that there may exist light, scalar or pseudoscalar, weakly interacting bosons. Generally the masses and the coupling of these particles to nucleons, leptons, and photons are not predicted by the proposed models. The most attractive solution of the strong CP problem is the existence of a light pseudoscalar boson - the axion [5]. The axion may have a priori mass in a very large range, namely ($10^{-12} < m_a < 10^6$) eV. The main part of this mass range from both – low and high mass boundaries – was excluded as a result of numerous experiments and constraints from astrophysical considerations [6, 7]. Astrophysical bounds are based on some assumptions concerning the axion and photon fluxes produced in stellar plasma. These more recent constraints limit the axion mass to ($10^{-5} < m_a < 10^{-3}$) eV with small coupling constants to quarks and photon [6, 7, 8]. Although these limits are more stringent than can be reached in laboratory experiments, it is of interest to try to constrain the axion as much as possible using laboratory means. The laboratory experiments performed or proposed so far are rather diverse and employ a variety of detection techniques. The interpretation of laboratory experiments depend on less number of assumptions than the constraints inferred from astrophysical and cosmological observations and calculations. Axion is one of the best candidates for the cold dark matter of the Universe [9].

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Axions mediate a P- and T-reversal violating monopole-dipole interaction potential between spin and matter (polarized and unpolarized nucleons) [10]:

$$V(\mathbf{r}) = \boldsymbol{\sigma} \cdot \mathbf{n} g_s g_p \kappa \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}, \quad (1)$$

where g_s and g_p are the dimensionless coupling constants of the scalar and pseudoscalar vertices (unpolarized and polarized particles), $\kappa = \hbar^2/(8\pi m_n)$, m_n is the nucleon mass at the polarized vertex, $\boldsymbol{\sigma}$ is the Pauli matrix related to spin of polarized nucleon, r is the distance between the nucleons, $\lambda = \hbar/(m_a c)$ is the range of the force, m_a - the axion mass, and $\mathbf{n} = \mathbf{r}/r$ is the unitary vector directed from polarized nucleon to unpolarized one.

The potential between the layer of substance and the nucleon separated by the distance x from the surface is:

$$V(x) = \mp 2\pi g_s g_p \kappa \lambda N e^{-x/\lambda} (1 - e^{-d/\lambda}), \quad (2)$$

where N is the nucleon density in the layer, d is the layer's thickness. The “-” and “+” depend on the nucleon spin projection on x-axis (the surface normal).

Several laboratory searches provided constraints on axion-like coupling in the macroscopic range $\lambda > 0.1$ cm [7].

The limit on this interaction in the λ -range ($10^{-4} - 1$) cm was established in the Stern-Gerlach type experiment in which ultracold neutrons (UCN) transmitted through a slit between a horizontal mirror and absorber [11]. The obtained limit for the value $g_s g_p$ was $\sim 10^{-15}$ at $\lambda = 10^{-2}$ cm. This limit corresponds to the value of the monopole-dipole potential at the surface of the mirror $\sim 10^{-3}$ neV, which is equivalent to the magnetic field of ~ 0.2 G in the interaction μH of the neutron magnetic moment with magnetic field.

Sensitivity estimates for a future ultracold neutron Stern-Gerlach type experiment were presented, which promise orders of magnitude improvements in limiting the monopole-dipole interaction [12].

There was also a proposal of the ultracold neutron magnetic resonance frequency shift experiment for obtaining these constraints with better precision [13].

It is shown here that constraints on this type of interaction may be obtained from the existing experimental data on spin relaxation of polarized ${}^3\text{He}$.

First, we consider a simple case of an infinite flat ${}^3\text{He}$ cell. Two walls of this cell, in which polarized ${}^3\text{He}$ gas is contained between layers of thickness d , produce gradient of spin dependent potential:

$$\frac{\partial V}{\partial x} = \pm 2\pi g_s g_p \kappa N (1 - e^{-d/\lambda}) (e^{-x/\lambda} + e^{(x-L)/\lambda}), \quad (3)$$

where L is the distance between the walls (center of the cell is at $x = L/2$).

The interaction energy μH of the particle magnetic moment in a magnetic field is similar to the interaction energy $\boldsymbol{\sigma} \mathbf{H}^*$ of the particle spin in the pseudo-magnetic monopole-dipole field \mathbf{H}^*

induced by nucleons in a substance. The action of the gradient of this field on the spin of polarized ^3He is equivalent to the action of the gradient of the magnetic field on the magnetic moment.

It is known that translational diffusion of polarized particles in the chaotic magnetic fields affects significantly spin-relaxation, resulting in the shortening of the spin-relaxation time. Physically it is explained by the fact that when a polarized particle undergoes chaotic Brownian motion in the region of the magnetic field gradients, it experiences randomly fluctuating magnetic fields. Spin-relaxation of atomic nuclei in gas depends strongly on these fluctuations. The expression for the longitudinal spin-relaxation time T_1 in an inhomogeneous magnetic field has been obtained in a number of works (see [14] and references therein). The rate of spin relaxation of ^3He nuclei polarized along z-axis in the gradient of magnetic field is

$$\frac{1}{T_1^{grad}} = \frac{1}{3} \frac{(\partial H_x / \partial x)^2 + (\partial H_y / \partial y)^2}{H_z^2} \langle u^2 \rangle \frac{\tau_c}{1 + (\omega_0 \tau_c)^2}, \quad (4)$$

where $\langle u^2 \rangle$ is the mean squared velocity of ^3He atoms in a gas, $\omega_0 = 2\mu H_z / \hbar$ is the magnetic resonance frequency in the magnetic field applied along z-axis, τ_c is the time between collisions of the ^3He atoms in a gas.

More general formula was derived in [15] also valid at low magnetic fields and low pressures. The critical parameter introduced in this work: $\omega_0 R^2 / D$, where R is the size of a cell, $D = u^2 \tau_c / 3$ is the ^3He diffusion coefficient in a gas, is $\sim 10^6$ in the experiments used to infer the constraints on the axion-like coupling, and is very large at any reasonable cell size and gas pressure. At large values of this parameter Eq. (4) is valid.

When spin relaxation is caused by the gradient of spin-dependent potential V , the rate of spin relaxation is

$$\frac{1}{T_1^{grad}} = \frac{4}{3} \frac{(\partial V_x / \partial x)^2 + (\partial V_y / \partial y)^2}{(\hbar \omega_0)^2} \langle u^2 \rangle \frac{\tau_c}{1 + (\omega_0 \tau_c)^2}. \quad (5)$$

For an infinite flat cell $V_y = 0$. Averaging over the cell width gives (at $\omega_0 \tau_c \ll 1$):

$$\frac{1}{T_1^{grad}} = \frac{4}{3} \frac{(g_s g_p \kappa N)^2 \langle u^2 \rangle \tau_c}{(\hbar \omega_0)^2} G_{inf}, \quad (6)$$

where

$$G_{inf} = \frac{(2\pi)^2 (1 - e^{-d/\lambda})^2 \lambda}{L} \left(1 - e^{-2L/\lambda} + \frac{2L}{\lambda} e^{-L/\lambda} \right). \quad (7)$$

It follows from Eqs. (3-7):

$$g_s g_p = \left(\frac{3}{4} \right)^{1/2} \frac{\hbar \omega_0}{\kappa N (\langle u^2 \rangle \tau_c G_{inf} T_1^{grad})^{1/2}}. \quad (8)$$

For a finite cylindrical cell both $\partial V_x / \partial x$ and $\partial V_y / \partial y$ components of pseudomagnetic potential are essential.

For a disc of radius R and thickness d with its axis along x-axis, the potential at the point \mathbf{r} is (Fig. 1):

$$V_x^{Idisc}(\mathbf{r}) = g_s g_p \kappa N \int_0^{2\pi} d\varphi \int_0^R \rho d\rho \int_0^d dt \frac{-(x+t)}{q^2} \left(\frac{1}{\lambda} + \frac{1}{q} \right) e^{-q/\lambda},$$

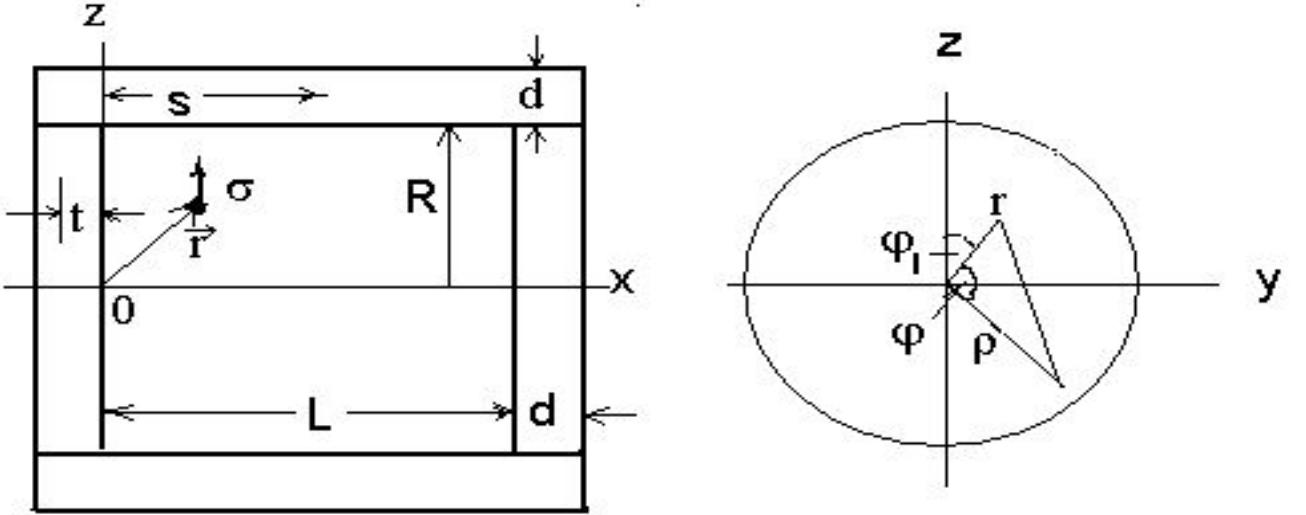


Figure 1: Geometry of a cylindrical cell used in calculations of G_{cyl} .

$$V_y^{Idisc}(\mathbf{r}) = g_s g_p \kappa N \int_0^{2\pi} d\varphi \int_0^R \rho d\rho \int_0^d dt \frac{\beta}{q^2} \left(\frac{1}{\lambda} + \frac{1}{q} \right) e^{-q/\lambda}, \quad (9)$$

where $q = (r^2 + \rho^2 - 2r\rho \cos \varphi + (x + t)^2)^{1/2}$ is the distance from the spin to the nucleus, t is the distance from the disc surface to the nucleus, $r = (y^2 + z^2)^{1/2}$ is the projection of the radius-vector \mathbf{r} of the spin on the yz -plane, φ_1 is the angle between this projection and the z -axis, ρ is the projection of the radius-vector of the nucleus on the y, z -plane, φ is the angle between r and ρ , $\beta = \rho(\sin(\varphi_1 + \varphi) + \cos(\varphi_1 + \varphi)) - r(\sin \varphi_1 + \cos \varphi_1)$.

For the second disc of the cell $-(x + t)$ is replaced by $(L - x + t)$.

For a cylinder wall of internal radius R , length $L + 2d$ and wall thickness d

$$\begin{aligned} V_x^{cyl}(\mathbf{r}) &= g_s g_p \kappa \int_0^{2\pi} d\varphi \int_R^{R+d} \rho d\rho \int_{-d}^{L+d} ds \frac{s - x}{q^2} \left(\frac{1}{\lambda} + \frac{1}{q} \right) e^{-q/\lambda}, \\ V_y^{cyl}(\mathbf{r}) &= g_s g_p \kappa \int_0^{2\pi} d\varphi \int_R^{R+d} \rho d\rho \int_{-d}^{L+d} ds \frac{\beta}{q^2} \left(\frac{1}{\lambda} + \frac{1}{q} \right) e^{-q/\lambda}. \end{aligned} \quad (10)$$

The derivatives of these potentials are the sums of contributions from all walls of a cylindrical cell:

$$\frac{\partial V_x(\mathbf{r})}{\partial x} = \frac{\partial V_x^{Idisc}(\mathbf{r})}{\partial x} + \frac{\partial V_x^{IIdisc}(\mathbf{r})}{\partial x} + \frac{\partial V_x^{cyl}(\mathbf{r})}{\partial x},$$

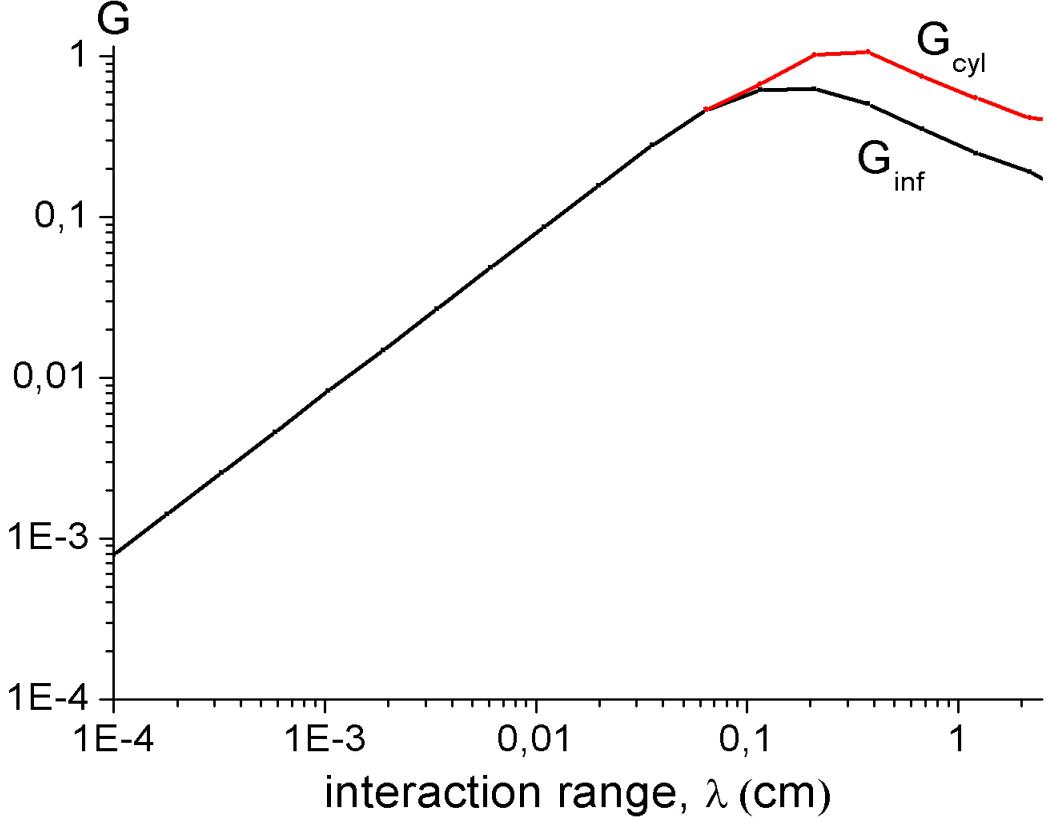


Figure 2: Calculated G_{inf} (Eq. (7)) and G_{cyl} (Eq. (12)).

$$\frac{\partial V_y(\mathbf{r})}{\partial y} = \frac{\partial V_y^{Idisc}(\mathbf{r})}{\partial y} + \frac{\partial V_y^{IIdisc}(\mathbf{r})}{\partial y} + \frac{\partial V_y^{cyl}(\mathbf{r})}{\partial y}. \quad (11)$$

The sum of the squares of gradients averaged over the volume of the cylindrical cell is

$$\left\langle \left(\frac{\partial V_x}{\partial x} \right)^2 + \left(\frac{\partial V_y}{\partial y} \right)^2 \right\rangle = \frac{(g_s g_p \kappa N)^2}{V_{cell}} \int_0^{2\pi} d\varphi_1 \int_0^R r dr \int_0^L dx \left[\left(\frac{\partial V_x(\mathbf{r})}{\partial x} \right)^2 + \left(\frac{\partial V_y(\mathbf{r})}{\partial y} \right)^2 \right] = (g_s g_p \kappa N)^2 G_{cyl}. \quad (12)$$

The results of computation of G_{cyl} when $R=2.5$ cm, $L=5$ cm and $d=0.2$ cm are shown in Fig. 2 together with G_{inf} at $L=5$ cm and $d=0.2$ cm. It is seen that they coincide when $\lambda \ll R, L$.

Similarly to Eq. (6) for a cylindrical cell we have

$$\frac{1}{T_1^{grad}} = \frac{4}{3} \frac{(g_s g_p \kappa N)^2 \langle u^2 \rangle \tau_c}{(\hbar \omega_0)^2} G_{cyl} \quad (13)$$

and

$$g_s g_p = \left(\frac{3}{4} \right)^{1/2} \frac{\hbar \omega_0}{\kappa N (\langle u^2 \rangle \tau_c G_{cyl} T_1^{grad})^{1/2}}. \quad (14)$$

Usually large variations of the ${}^3\text{He}$ spin relaxation time are observed among cells. For obtaining constraints for the monopole-dipole coupling we consider here the results of recent measurements of the ${}^3\text{He}$ spin relaxation [16, 17, 18, 19] in which the largest values of T_1 were demonstrated.

The cylindrical cell "1" [16] has dimensions: diameter 4×5 cm, ^3He pressure of 0.78 bar (corrected [19] compared to 0.85 bar in the publication [16]), and the spin relaxation time $T_1^{exp} = 840 \pm 16$ hours.

The cell "Diamond" [19] has spherical form, diameter 3 cm, ^3He pressure of 0.13 bar plus 0.9 bar of ^4He , and the spin relaxation time $T_1^{exp} = 3000 \pm 500$ hours.

The cylindrical cell "j1" [18] has dimensions: diameter 5×5 cm, pressure of 0.93 bar (corrected [20] compared to 0.97 bar in the publication [18]), and spin relaxation time $T_1^{exp} = 663 \pm 7$ hours.

The experimental spin relaxation time is determined by the contributions from several random processes of time independent relaxation, the total relaxation rate is the sum of rates for each process:

$$\frac{1}{T_1^{exp}} = \frac{1}{T_1^{dip-dip}} + \frac{1}{T_1^{wall}} + \frac{1}{T_1^{inhom}} + \frac{1}{T_1^{unknown}}, \quad (15)$$

where $T_1^{dip-dip}$ is the bulk dipole-dipole relaxation time, T_1^{wall} is due to the ^3He spin relaxation on the walls of the cell, T_1^{inhom} is due to the magnetic field inhomogeneities, $T_1^{unknown}$ may be determined by unknown factors.

According to the calculations by Newbury et al. [21] of the magnetic-dipole interaction between nuclear spins in the ^3He gas $T_1^{dip-dip} = 807/P$ hours, where P is the ^3He pressure in bar for a temperature of 296 K. The precision of these calculations according to [22, 23] was about 1%. Possible contribution of any nonmagnetic dipole-dipole interaction between ^3He atoms is small compared to this uncertainty [24, 25].

We use here the published data for cylindrical cells of Refs. [16] and [18]. The appropriate dipole-dipole relaxation rate has been subtracted from these data. After this subtraction the remaining relaxation time is $T_1^{rem} = 4466 \pm 245$ hours for Ref. [16], and $T_1^{rem} = 2810 \pm 146$ hours for Ref. [18]. In the calculation of uncertainties of T_1^{rem} it was assumed that the errors in the ^3He pressure measurements performed by the neutron transmission were about 5% [19, 22]. As is seen, the remaining relaxation times for these cells are not significantly different.

These values of T_1^{rem} were used for obtaining constraints on the monopole-dipole interaction, the unknown value of wall relaxation rate being attributed to the effect of the monopole-dipole potential. Magnetic field inhomogeneities in these measurements were very small but not exactly known, their effect on spin relaxation was also attributed to the effect of the monopole-dipole potential.

Taking $\langle u^2 \rangle = 3kT/m_{^3\text{He}} = 2.35 \times 10^{10} (\text{cm/s})^2$, $\tau_c = 3 \times 10^{-10} \text{ s}$ [21], $\omega_0 = 10^5 \text{ s}^{-1}$, ($H_z = 10 \text{ G}$, the gyromagnetic ratio $\gamma_{^3\text{He}} = 1.62 \text{ kHz/G}$), $N = 1.5 \times 10^{24} \text{ cm}^{-3}$, the thickness of the glass walls of the cell $d=0.2 \text{ cm}$, the width of the cell $L=5 \text{ cm}$ [18], we get

$$g_s g_p \approx \frac{8.4 \times 10^{-16}}{(G_{cyl} T_1^{rem})^{1/2}}. \quad (16)$$

The obtained constraints are shown in Fig. 3 together with the constraints known from other sources.

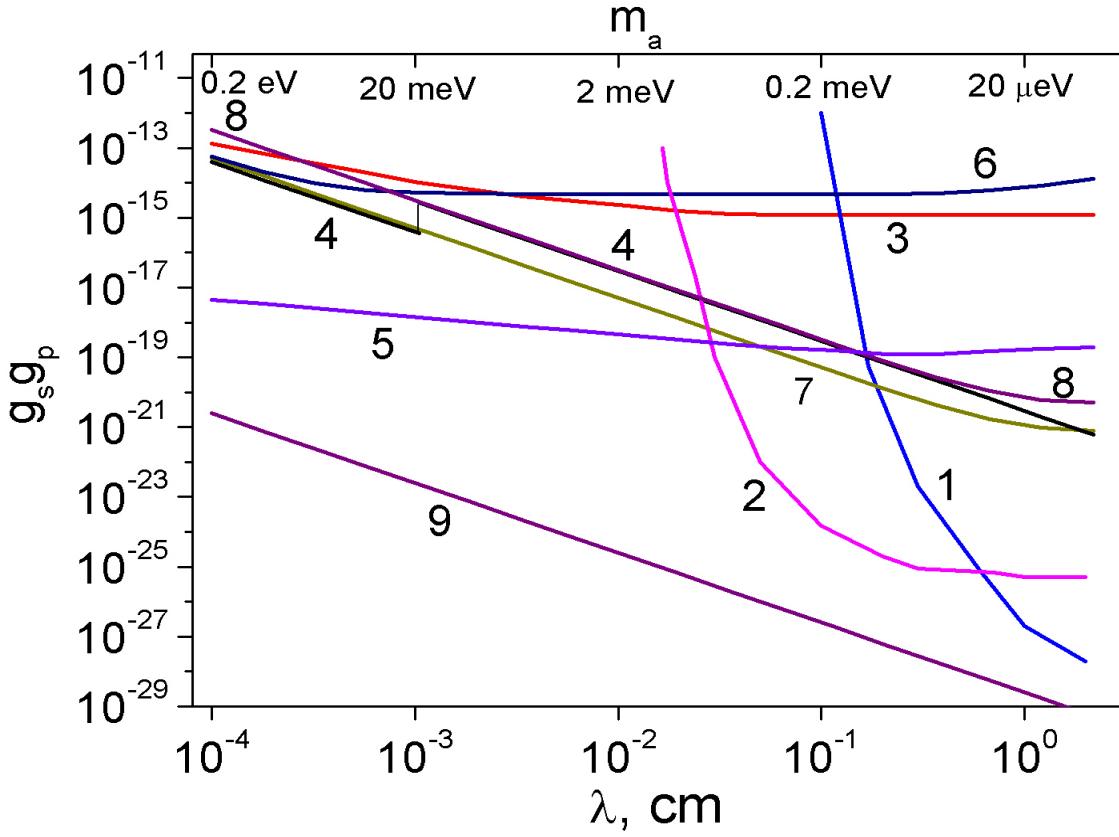


Figure 3: Constraints on the axion monopole-dipole coupling strength $g_s g_p$ and effective range λ : 1 and 2 - constraints for the value of coupling constant of nucleon and electron $g_s^n g_p^e$ from Refs. [26] and [27], respectively; 3 - from the UCN Stern-Gerlach experiment [11]; 4 - from the UCN depolarization probability according to [28]; 5 - from spin relaxation of 3He , this work; 6, 7, and 8 - from the UCN depolarization probability [29], in different assumptions regarding the experimental conditions of the UCN depolarization measurement; 9 - from the product of separate constraints for g_s from gravitational experiments of the Seattle [30, 31, 32] and Stanford [33, 34, 35] groups, and astrophysical constraints on g_p [36, 7].

The value of $T_1^{rem}=2518$ hours was used here – two standard errors less than the mean remaining longitudinal relaxation time from the measurements [18].

These ^3He relaxation time data may be used to set limits on the monopole-dipole coupling between nucleon spins of the ^3He nuclei and electrons of the walls of the cell. The density of electrons in the medium is approximately two times lower than the density of nucleons, therefore the constraints are respectively two times less strong.

These constraints should be improved in dedicated experiments with polarized ^3He gas. First, if the wall relaxation could be further decreased, better sensitivity would be obtained to additional sources of spin relaxation in the ^3He cells. At lower gas pressure the time between atom collisions τ_c is larger, which gives better sensitivity, but at the condition, that the free path length between atom collisions in the gas cell $u\tau_c \ll \lambda$. The geometry of a cell may be optimized for the chosen interaction range λ . Generally, it would be good to use the narrowest possible cell, for large λ to place additional mass with the largest nucleon density in close vicinity to the walls of a cell. In the limit $d \gg \lambda \gg R, L$ we have $G_{inf} \rightarrow (4\pi)^2$. The sensitivity is increased also if to decrease the guiding magnetic field H_z .

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